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A MATHEMATICAL MODEL OF BLIND MOBILITY

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DSR 70249-2

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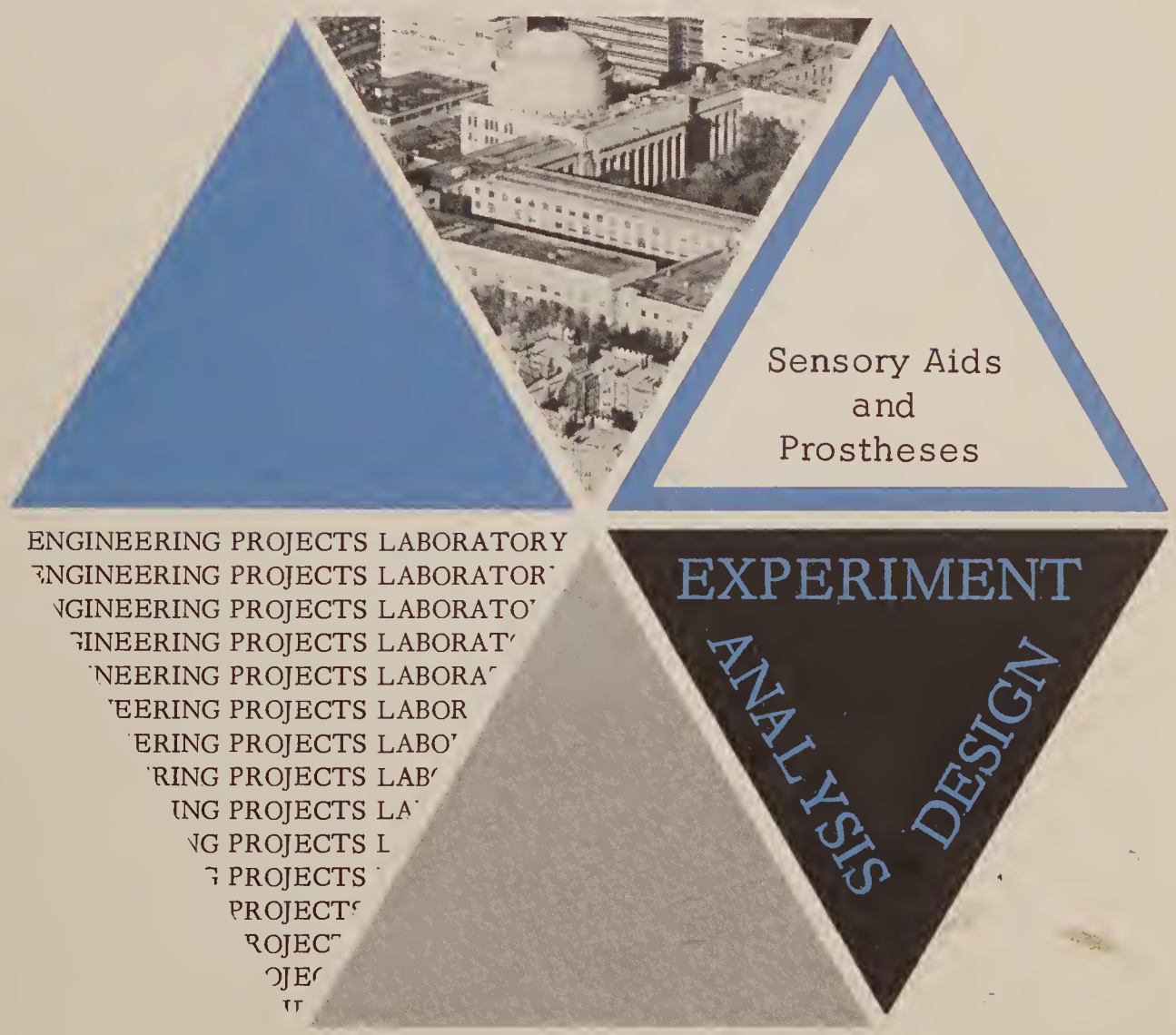

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by

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EPL Report No. 70249-2

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April 1967

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PREFACE

Since 1959 the Sensory Aids and Prosthetics Project of the Engineering Projects Laboratory and Department of Mechanical Engineering, M.I.T., has involved undergraduate and graduate students, under the supervision of Professors Dwight M. Baumann, Robert W. Mann, Thomas B. Sheridan, and W. Russell Ferrell on a succession of projects applying engineering research and development to the definition and creation of technology-based assists to the blind.

The work can be catagorized into research on perception, exploring the alternative tactile and aural channels still available to the blind, research on blind mobility and the development of devices to enhance the travel of the blind, and research and development on means of increasing the blind's access to the printed page and other written communication.

The sensory aids effort is complemented by research and development on limb and skeletal prostheses and ortheses. Since the research interests of both programs overlap and reinforce each other, and both involve some of the same personnel, facilities and support, a single bibliography combines both sensory aids and prostheses publications.

For most of the studies the basic resource document is the original Bachelor's, Master's and Doctoral theses, available for reference or photocopy in the M.I.T. Library or by ozalid copy from the EPL Document Room, 3-156, M.I.T. Papers published in the Journals of Professional Societies and Organizations also represent a source of fundamental and interpretive information on the program. For those

investigations which have not culminated in either thesis or professional publication, Engineering Project Laboratory reports are prepared and circulated, as for example, this report "A Mathematical Model of Blind Mobility". The Bibliography appended to this report lists the title, author and source of all theses, papers and reports prepared by members of the Sensory Aids and Prosthetics Group.

Major support for the program has been provided by the Vocational Rehabilitation Administration of the Department of Health, Education and Welfare. Supplementary grant-in-aid support from the American Foundation for the Blind, the Medical Foundation, Inc. of Boston, and the E. Matilda Ziegler Foundation of New York City are also gratefully acknowledged.

Robert W. Mann
Professor of Mechanical Engineering

INTRODUCTION

Incomplete understanding of the mobility process, perhaps more than technological limitations, has hampered the development of satisfactory mobility aids for the blind. Mann [1][1], for example, has noted that engineering problems associated with probing the environment for information, while by no means solved for the blind traveler, are within the realm of present electronic capability. It is the display and assimilation of the information which remains the crucial problem. He states, "Part of the display problem (and difficult of segregation from the art of beholding) is the discrimination in the field of view of objects of especial and timely interest for the blind man, i.e., the obstacles he must avoid or comply with".

Daniels [2] suggests that a hierarchy of decision rules may exist to guide the traveler through the dual mazes of objects and signals about objects. If such a set of rules existed and were understood, the traveler could be presented with processed rather than raw environmental data.

In an effort to gain more understanding of the process of mobility, whether of a blind or a sighted navigator, on foot or at the controls of a vehicle, a mathematical model of the mobility process has been proposed and investigated. It is hoped that such a model may lead to isolation of significant variables associated with mobility, and to comprehension of the interactions among these variables. Such comprehension in turn may lead to methods and

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[1] Numbers in brackets signify references given at the end of the report.

devices which present the blind traveler with information he can use to maneuver himself in a world shaped by the sighted.

ANALYTICAL MODEL

The Traveler as an Information Processor

The model proposed treats a traveler as a processor of information. Information is gathered with a probe (eye, cane, radar, etc.), is "used" in path traversal, and is "lost" in the uncertainties of memory decay and disorientation. The basis for the model is an equation which balances information gains and losses.

The following assumptions and idealizations are made.

a) the probe has a fixed range R

b) the path scanned has width L

c) the path may be characterized by a constant information density n bits/area

d) the traveler maintains a constant velocity V

e) there is a uniform weighting of the information received by the probe from various distances

f) uncertainty due to memory and orientation increase exponentially with time, and may be combined into a single term with time constant 1/K.

Reaction time and stopping distance undoubtedly have an effect on performance. These have not been considered in the present model in order that the information variables stand out more clearly. In all the experimental investigations with walking subjects, the reaction and dynamics were assumed uniform and therefore not to introduce spurious data. The form of the probe assumed for the model has an effect on the relationships evolved. Two types of probes have been considered.

In the scanning probe, a narrow beam searches the path by moving transverse to the direction of travel. A full-field probe, on the other hand, covers the entire path width.

Scanning Probe

This probe will be idealized as a beam of width $d\ell$, scanning with speed S normal to the direction of travel. As he moves along the path, in the time T required for a single probe sweep, the traveler traverses an area equal to LVT. In doing so, he "uses" H* bits of information, where

$$H^* = nLVT \tag{1}$$

The information, H, available to the traveler at the end of each sweep, assuming no carry-over from previous sweeps, is found by integrating

$$dH = nRd\ell e^{-K(T-t)} \tag{2}$$

over the cycle. Since $\ell = St$, this yields

$$H = nRSe^{-KT} \int_0^T e^{Kt} dt \tag{3}$$

$$H = \frac{nRS}{K} (1 - e^{-KT})$$

If the use of information is limited by the amount available, the condition for travel is $H^* \leq H$. Using the equality as a limit,

$$V = \frac{RS^2}{KL^2} [1 - e^{-(KL/S)}] \tag{4}$$

or

$$V = \frac{R}{KT^2}\left[1 - e^{-KT}\right] \tag{5}$$

The following limiting cases are of interest.

a)	$\lim V = 0$	memory and orientation uncertainties
	$K \to \infty$	are preponderant, traveler goes very slowly
b)	$\lim V = R/T$	no uncertainties are present, velocity
	$K \to 0$	is limited only by probing ability
c)	$\lim V = 0$	slowness of the probing allows finite
	$T \to \infty$	memory and orientation uncertainty to dominate
d)	$\lim V = \infty$	fast sweep yields such large information
	$T \to 0$	transmission that velocity is not limited by lack of information.

Full-Field Probes

This probe will be idealized as a beam of width L which has a sampling cycle consisting of t active time units followed by τ non-active time units. During the active portion of the cycle, the information collected is

$$H = nLR + nLVt \quad \text{bits} \tag{6}$$

The information used during the entire cycle is

$$H^* = nLV(t + \tau) \tag{7}$$

The amount of information lost to decay during the non-active portion of the cycle is

$$H_L = (nLR + nLVt)[1 - e^{-K\tau}] \tag{8}$$

Therefore, the information available at the end of a cycle is $H - H_L$. For travel $(H - H_L) \leq H^*$. If the equality is taken as a limit,

$$V = \frac{Re^{-K\tau}}{\tau + t(1 - e^{-K\tau})} \tag{9}$$

The following limiting cases are of interest.

a)	$\lim V = 0$ $K \to \infty$	memory and orientation uncertainties are preponderant, traveler goes very slowly
b)	$\lim V = R/(t + \tau)$ $K \to 0$	no uncertainties are present, velocity is limited only by probe range and cycle time
c)	$\lim V \to 0$ $\tau \to \infty$	if probe is always inactive, velocity is zero because no information reaches traveler
d)	$\lim V \to \infty$ $\tau \to 0$	if probe is always active, information is unlimited and velocity not bounded by lack of information.

Discussion of Analytical Results

The equations resulting from the analysis above are different for the two types of probes - but have the following similarities.

1. The limiting velocities for the memory-orientation time constant, K, approaching both zero and infinity are the same for the two probes, as are the limiting velocities for both zero and infinite probe search periods.

2. For both probes, $\frac{\partial V}{\partial R}$ = constant.

3. For the scanning probe, $\lim_{K \to 0} \frac{\partial V}{\partial K} = R$ while for the full field probe, $\lim_{K \to 0} \frac{\partial V}{\partial K} = R(1 + \frac{t}{\tau})$ - which results are, at least, comparable.

4. Velocity is independent of information density in both equations.

EXPERIMENTAL INVESTIGATION

Four sets of experiments have been conducted to date in order to examine the predictions of the information model. For one of these sets, an optical tracking device has been built, on which further work is anticipated.

The experiments are summarized for reference in Table I.

Experiment I

The first set of experiments was performed at M.I.T. in May 1965. The purpose was to test the prediction that velocity was not a function of information density, and to investigate the effects of memory and orientation on performance.

The experiment was run in two series, consisting of four and six tasks each, as indicated in Table I. In every case, a normally sighted subject walked along a 120 foot straight-line course with

EXPERIMENT SET	SERIES	EFFECTS OR RELATIONS INVESTIGATED
I	1. Four course negotiation tasks, normal subjects, eyes closed 2. Six course negotiation tasks, normal subjects, eyes closed. Auditory cues suppressed in three of the tasks.	Independence of velocity from information density; presence of memory and orientation effects in measured performance.
II	1. Course negotiation with objects as travel guides. Normal subjects, blind-folded.	Effect of object density on travel
	2. Course negotiation with auditory signal to warn of obstacles within range. Normal subjects, blind-folded.	Effect of probe range and warning signal duration.
	3. Goal attainment, with circumnavigation of large objects. Normal subjects, blindfolded.	Relation of orientation to travel
III	1. Course negotiation with auditory signal to warn of obstacles within range. Congenitally blind subjects.	Effect of probe range and warning signal duration.
	2. Goal attainment with circumnavigation of large objects. Congenitally blind subjects.	Relation of orientation to travel.
IV	Use of travel simulator, the self-paced tracker.	Effect of path complexity, probe range, and scan duration

TABLE I

SUMMARY OF EXPERIMENTS

his eyes closed. Lightweight plastic chairs were placed as objects along the course. The assumption was made that the number of chairs was a measure of path information density. Subjects were told that their performance would be measured by their speed, their accuracy, and their behavior at object encounter; in actuality, only speed was used. A description of tasks, by series, is given in Table II.

Six subjects were used in series 1, and three in series 2. A single object density was used for each subject.

A tabulation of the average velocity for each subject as a function of the number of objects in his path may be found in Appendix A. The Pearson product-moment coefficient of correlation [3] between object density and velocity may be found to be r = 0.160. This is a low enough coefficient to support belief in the independence of velocity from object density.

A tabulation of the average velocity of each subject by task may also be found in the appendix.

An analysis of the variance of this data by task, using the Snedecor F test, shows that the differences in series 1 are significant at the .001 level. This indicates that memory and orientation effects may be significant - but the nature of this experiment does not allow a quantitative estimate to be made of the time constant in the model.

A similar analysis of the differences in series 2 indicates a much lower level of significance (.25), which may be due to the lack of significance of the use of auditory cues.

SERIES	TASK	CONDITIONS
I	1-a	Unobstructed course
	1-b	Objects viewed prior to course negotiation
	1-c	Objects not viewed prior to course negotiation
	1-d	Orientation aided by string at chest height stretched above straight line along course.
2	2-a	Unobstructed course (same as 1-a)
	2-b	Unobstructed course, with ear protectors used on subjects to suppress auditory cues
	2-c	Objects viewed prior to course negotiation (same as 1-b)
	2-d	Objects viewed prior to course negotiation. Ear protectors used to suppress auditory cues
	2-e	Objects not viewed prior to course negotiation (same as 1-c)
	2-f	Objects not viewed prior to course negotiation. Ear protectors used to suppress auditory cues.

TABLE II

SUMMARY OF TASKS IN EXPERIMENT I

Experiment II

The second set of experiments was performed at Clarkson College in April 1966.[2] This set consisted of three basic experimental series, principally concerned with object density, probe range, and orientation respectively, as indicated in Table I.

The first series was designed to test the effect of object density on travel. Normally sighted subjects walked blind-folded along a course following the corridors of a building from the ground floor, through the first, to the second story. Objects were placed along the intended path to serve as travel guides. For example, the arms of students chairs indicated the intended direction of travel, tables warned of stairways down, stools of stairways up. Each object was placed at the vertex of a triangular paper taped to the floor, the purpose of which was to signal the presence of the object.

A minimum set of objects consisted of chairs at the origin of each turn, plus tables and stools at the stairways.

Three subjects were each tested with three object densities. The principle data was in the form of marks on a map of the course showing the position of the subject at five second intervals. From the maps, average velocities for the course, and corrected average velocities - compensating for the time devoted to object negotiation - could be calculated.

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[2] The second and third sets of experiments were conducted in conjunction with a course entitled: Human Factors in Engineering, given by the author at Clarkson College in the spring semester, 1966.

A Friedman two-way analysis of variance [4] in the traversal times, both total and compensated, indicated that no significant differences in velocities existed among the three object densities.

The data was further investigated to study the effect of object density on traveler confidence. Velocity was considered one measure of confidence - but, in addition, the time spent investigating an object and the time spent in hesitation during the run were assumed to be confidence measures. A two way analysis of variance on this data also indicated that the differences due to different object densities were not significant.

This series of experiments yields results which agree with the predictions of the model. It is possible, however, that the object density was too high to achieve significant results. Longer distance between objects, i.e. a lower information density, might have revealed an information threshold level.

The second series in the experiment set was designed to investigate the effect of probe range and warning signal duration on travel. Subjects walked blindfolded along a nine-foot wide, 120-foot long, section of building corridor. Chairs were arranged in lines normal to the direction of travel. A portable electric bell was used as the warning device and sounded by the experimenters when the subject came to the appropriate distance from an object. Warnings were given for two "probe" ranges - namely four feet and eight feet - and were of two durations - a short pulse sounded as the subject entered the "collision zone", or a continuous signal, lasting as long as the subject remained in range of the object.

Four subjects had four runs each corresponding to the 2 x 2 matrix of the above conditions summarized as Table III.

Four foot probe range Short warning pulse	Four foot probe range Continuous warning signal
Eight foot probe range Short warning pulse	Eight foot probe range Continuous warning signal

TABLE III

EXPERIMENTAL CONDITIONS,
EXPERIMENT SET II, SERIES 2

The data taken was the time at which the subject left an object, reached a warning line, and reached an object.

A Friedman two-way analysis of variance by ranks, performed on average velocities, indicates that there is no significance to the differences among the four experimental conditions, indicating that velocity is not dependent on probe range in the ranges investigated.

If the data is re-cast into two categories rather than four, viz., four foot vs. eight foot probes, irrespective of the type of warning, the differences become more significant, with the greater warning distances giving rise to higher velocities. This is especially marked in the collision zone velocities, and therefore

might be a manifestation of measuring an inherent weighting factor in object encounter over different distances.

An interesting result is the fact that when data is cast into a form to distinguish between the short pulse and continuous warning - analysis yields no indication of significant difference. This suggests that an object detecting aid need not necessarily give a sustained warning, as many present models and proposals do. This can lead to a saving of power and less possibility of masking the audial channel to other signals.

The third series of experiments was designed to study the relationship between orientation and travel. An electric buzzer was sounded at one end of a gymnasium, blindfolded subjects were started at various points along the opposite end and told to walk toward the sound source. On the floor of the gym were "islands" of wrestling mats on which the subjects were not to walk. Subjects were to try to reach the buzzer in spite of innate disorienting effects and those introduced by circumnavigation of large objects. In the "machine paced" trials, the buzzer sounded periodically for orientation purposes, in the "self-paced" trials, the subject could ask for a signal by raising his arm.

Time was recorded for inter-object travel and for obstacle negotiation, and the travel path was marked on a map of the test area. The speed, travel distance divided by travel time could be found, and used as a measure of confidence. Actual distances were considered to be measures of accuracy, the more circuitous routes being the less accurate.

An analysis of the data reveals that the differences in velocity achieved due to different signal rates were not significant, nor were differences in accuracy. The subjects' levels of achievement, furthermore, were substantially the same in the self-paced trials as in the machine paced.

The subjects' measurable performances were therefore relatively insensitive to the amount of information supplied to them from the signalling device. This may be due to a sense of orientation better than we had anticipated, or to the use of other cues. In either case, there is an indication that visually deprived individuals may need only minor aid to their normal orientation.

It might be noted that one subject, who was able to navigate the course with no signals following the initial sound in three self-paced runs became disoriented in her fourth trial, and asked for three additional signals. No other subject required more than one plus two signals. This suggests that a subject, once disoriented, requires considerable assistance.

Experiment III

The third set of experiments was conducted in May, 1966 at the Montreal Association School for the Blind in Montreal, Quebec. Subjects were four totally blind children between the ages of 8-11 years. This set of experiments was similar to the set described directly above. It was designed to investigate the effect of probe range and of orientation on the travel process, and to test the hypothesis that the performance of the blind children would not be significantly different from that of the sighted subjects previously used.

In the first experiment, obstacles, made of chairs, play-boxes, etc. were arranged on an outdoor course 242 feet long and 13 feet wide. The course ran north and south, with a sidewalk as the west and a string as the east boundary. A warning bell was sounded, to simulate a probe, as the subject came into range of the object. Two ranges were selected for each subject, namely three and nine feet. Because of the results of the previous experiment, the warning signal was given for one second -- as the subject entered the collision zone.

In their practice sessions, the subjects were familiarized with the boundaries and were instructed to move back toward the center in the event of encounter. If a subject missed an obstacle, after having been given the warning signal, he was told that he had passed it.

The average velocities, both in and out of the collision zone were higher for the nine-foot warning than for the three. But the "t" test of significance between two sample means failed to find the differences significant at the .05 level.

In the second experiment, an outdoor course 200 feet by 45 feet was laid out. A series of large obstacles was spread about the course. The subjects were instructed to attempt to reach a goal -- again, an electric bell -- guiding themselves around the obstacles. Information was presented using three rates, six, three, and two signals per minute, and in a self-paced mode, a signal elicited by a raised hand. Times and paths were recorded.

A Friedman two-way analysis of variance failed to show any significance in differences in travel times due to different information rates.

Experiment IV

The fourth set of experiments was performed during the summer of 1966 at M.I.T. These experiments were run on the self-paced tracking device designed by the author at M.I.T., and by Mr. Stefan Malek at Clarkson College.

The self-paced tracker is a mobility simulator in which the target, usually a path image, drawn on blank 33 mm photographic film, is projected onto a photosensitive target. The film is fed through a motorized strip film projector at a speed controlled by the subject. The left and right position of the target relative to the path is also controlled by the subject -- by means of a Selsyn-controlled mirror. The present version of the device has a single control lever -- with forward and back positions controlling fast and slow, and left and right determining sidewise motion of the path-target system. The device also has a relay-operated shutter in front of the lense to cut off the subject's view. This is controlled by a push button.

Tests were run on paths with three different levels of complexity. This was accomplished by designing the paths to have identical angle-turn characteristics, but to be of different widths. In the present case, the widths were one-half, one-fourth, and one-eighth of the view field -- corresponding to one, two, and three units of information. Three "probe range" values were used. This "range" corresponded to the length of path the subject saw in front of the

target. Additionally, four shutter rates plus a self-paced shutter control mode were used. These were: shutter open; open-one second, closed-one second; open-two seconds, closed-one second; and open-two seconds, closed-two seconds. In the self-paced mode, the subject opened the shutter when he wanted to view the target.

It should be noted that the position control of the system acted approximately like a proportional controller, while the velocity exhibited a first order response -- with a lower time constant on acceleration than deceleration.

In this experiment, the subjects' input signals to the controller were monitored as were signals indicating whether the path was on or off target, and whether the shutter was open or closed.

None of the differences in velocity due to the various experimental conditions appear to be significant. In the open shutter run, the tracking accuracy decreased with path complexity, but speed remained effectively uniform. In the self-paced trials, the subject tended to keep the shutter open most of the time -- and again let his accuracy vary in favor of a uniform velocity. In the machine-paced shutter trials, all trackers eventually adopted the tactic of pulsing the speed -- on during the view, off during the non-view part of the cycle. The average velocity still was relatively fixed. Accuracy during the non-view portion of the cycle was low -- but because of the instrumentation, was not measured.

One factor that was not included in the analysis and not compensated for in the system design, is the refractory period inherent in the human response. The system could be modified to allow for this through a longer preview distance or a shorter time

constant on the speed controller.

CONCLUSION

Points deduced from the experimental data and from observations made during the performance of the experiments are summarized in Table IV. Note that the deductions mentioned in the Table IV apply only to the particular experiments, and to the conditions under which the experiments were performed. No claims of generalization are made except as specifically discussed below.

The experiments tend to verify the prediction that velocity is independent of path complexity, but they do not substantiate the predicted relations between probe range and velocity or between orientation-memory decay and velocity. Instead, they tend to indicate that velocity is relatively independent of these factors. Some correlation between range and velocity was noted in the second and third experimental sets -- but observation of subject performance on the self-paced tracker leads to a suspicion that reaction time, coupled with the traveler's stopping dynamics, may be a controlling factor in mobility, contrary to the bumper-to-bumper driving techniques used by many modern drivers.

The orientation series in the first three experiment sets lead to the idea that visually deprived travelers are able to maintain a high degree of orientation, and that this need not become a limiting factor in the travel process. It remains to be ascertained how much conscious effort is devoted to maintaining orientation, and whether the effort required for satisfactory travel is excessive. In the experiments, of course, subjects were able to concentrate on their

Experiment Set	Series	Deductions
I Sighted subjects, eyes closed	1. Straight-line course	Velocity independent of object density; memory and orientation effects showed significance
	2. Straight-line course, auditory cues suppressed	Auditory cues were not significant
II Sighted subjects, blindfolded	1. Objects as travel guides	Velocity independent of object density
	2. Auditory warning of approaching objects	Velocity independent of probe range; continuous and pulse warnings had equivalent effects
	3. Orientation toward fixed goal	Subjects displayed excellent innate sense of orientations
III Blind subjects	1. Auditory warning of approaching objects	Velocity independent of probe range
	2. Orientation toward fixed goal	Subjects displayed excellent innate sense of orientation
IV	Self-paced tracking system	Accuracy sacrificed for speed

TABLE IV

orientation. Experimentation similar in form to the above, using the auxiliary task technique to measure expended mental effort might answer this question.

It also appears from observing the experiments that when the actual cost of inaccuracy is not too high (e.g., bumping into an object without incurring excessive pain, embarrassment, or damage; driving onto the shoulder of a road without damaging the car, the driver, or the driver's pride), travelers are willing to sacrifice accuracy for speed. In an independent experiment at an earlier stage of development of the self-paced tracker, Malek [5] found that a bell arranged to ring while the subject was off track produced anxiety and embarrassment--and decidedly lower speed. An innate cost function, such as that described by Sheridan [6], may therefore exist with several discrete values--triggered by the danger level of the stimuli.

Experiment II Series 1, involving the traveler's use of objects, as opposed to his encounter with obstacles, tends to reflect favorably on the information concept of travel. The minimum set of objects, as described, led to performance not exceeded with a larger number of guides. Some confusion, in fact, was exhibited by the subjects on encountering the redundant objects. The traveler may have been faced with the decision of whether the object contained new information or was redundant. A sighted traveler may unconsciously extract information from the environment as desired; a traveler who receives information in discrete portions may have to evaluate each message as it is presented.

Somewhat in accord with the findings of Cratty and Williams [7] with respect to veer from a straight line path, we found that in control runs in which subjects walked a 48 foot straight line, blindfolded, veer could be significant. Of four subjects tested two walked 48 feet with zero deviations, one with 2 feet deviation and one with 8 feet deviation.

In Cratty's work, substantially longer courses -- 200 yards -- were used, and all subjects veered appreciable distances. There is little doubt but that some orientation assistance is needed by a blind traveler, but, as stated above, this may be a small amount.

It is interesting to note that there was consistency in the accuracy of subjects in the control runs and in the actual experiment. The subject with the 8 foot deviation had the worst accuracy record in the orientation runs -- with an actual path length average of 147 feet, as compared with 137 feet for the subject with the 2 foot deviation, and 128 and 136 feet for those with zero deviation. It should be noted that the subjects with zero deviation during the control run and the best accuracy during the actual runs, were both females. One of the experimenters advanced the observation that the young ladies both walked by placing one foot in front of the other, while the male subjects walked by placing each foot in front of its own previous position. Whether this has any implications for training of the blind traveler remains to be seen, but it appears as an interesting possibility. A final observation was that in experiment II, series 2, a warning pulse, sounded when the subject reached "probe range" of an obstacle, had the same effect as a continuous signal, given from the moment that the subject entered the range until he had passed out of a zone in which

he would encounter the object (either by changing path or by going around it). This indicates, as discussed in the experimental sections, that warning devices for the blind might be designed to give only a warning pulse, in normal travel, thereby not keeping the attention of the traveler distracted from other potential cues.

In conclusion, it should be emphasized that the experiments conducted were designed to test various facets of the proposed information model of the mobility process. To some extent, this has been done. For example, there is reasonable evidence to support the independence of velocity on path complexity. While other aspects of the testing program have brought out interesting points, they have, as could be anticipated, raised more questions than they have answered. Detailed study of the results, moreover, has shown that, while the model was proposed for the general mobility process, more careful study of the sighted and partially sighted, congenitally and adventitiously blind is needed. The tests conducted in Montreal with the kind support of the Montreal Association School for the Blind were an attempt to show that the information usage of one group of blind children was not significantly different from that of the normally sighted college students used in the other tests. This was verified at a superficial level, but, as with the majority of the points investigated, a great deal of detailed and specific work remains to be done.

APPENDIX A

Average Velocity as a Function of Object Density

No. of Obj.	Aver. Vel.
4	1.73
4	1.99
4	1.65
5	=1.54
7	1.57
9	1.61
9	1.12
11	1.46
11	1.69

Average Velocities and Testing Order by Task

subject / task	a	b	c	d	e	f
1-a	2.50;1	2.00;3	2.55;2	2.26;4	2.12;2	1.90;1
1-b	1.58;2	1.11;1	1.36;3	1.41;1	1.95;4	1.56;2
1-c	1.38;4	0.94;2	1.56;4	1.46;3	1.18;1	1.53;3
1-d	1.44;3	1.31;4	1.71;1	1.85;2	1.68;3	1.20;4

subject / task	g	h	i
2-a	2.31;1	1.82;1	2.14;3
2-b	1.92;2	1.94;2	2.07;4
2-c	1.46;3	2.40;5	1.38;1
2-d	1.38;4	2.31;6	1.48;2
2-e	1.43;5	1.74;4	1.44;5
2-f	1.32;6	1.72;3	1.57;6

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